0 Introduction

This document is intended to define the standard reference systems realized by the International Earth Rotation and Reference Systems Service (IERS) and the models and procedures used for this purpose. It is a continuation of the series of documents begun with the Project MERIT (Monitor Earth Rotation and Intercompare the Techniques) Standards (Melbourne *et al.*, 1983) and continued with the IERS Standards (McCarthy, 1989; McCarthy, 1992) and IERS Conventions (McCarthy, 1996; McCarthy and Petit, 2004). The current issue of the IERS Conventions is called the IERS Conventions (2010).

The reference systems and procedures of the IERS are based on the resolutions of international scientific unions. The celestial system is based on IAU (International Astronomical Union) Resolution A4 (1991). It was officially initiated and named International Celestial Reference System (ICRS) by IAU Resolution B2 (1997) and its definition was further refined by IAU Resolution B1 (2000) and by IAU Resolution B3 (2009). The terrestrial system is based on IUGG (International Union of Geodesy and Geophysics) Resolution 2 (1991). It was officially endorsed as the International Terrestrial Reference System (ITRS) by IUGG Resolution 2 (2007). The transformation between celestial and terrestrial systems is based on IAU Resolution B1 (2000) and was complemented by IAU Resolutions B1 and B2 (2006). The definition of time coordinates and time transformations, the models for light propagation and the motion of massive bodies are based on IAU Resolution A4 (1991), further refined by IAU Resolution B1 (2000) and IAU Resolution B3 (2006). In some cases, the procedures used by the IERS, and the resulting conventional frames produced by the IERS, do not completely follow these resolutions. These cases are identified in this document and procedures to obtain results consistent with the resolutions are indicated. Following IAU resolutions, the IERS reference systems are defined in the framework of the General Relativity Theory (GRT). In a few cases, models are expressed in the parameterized post-Newtonian (PPN) formalism using parameters β and γ (equal to 1 in GRT). These cases are identified with a note.

The units of length, mass, and time are in the International System of Units (Le Système International d'Unités (SI), 2006) as expressed by the meter (m), kilogram (kg) and second (s). The astronomical unit of time is the day containing 86400 SI seconds. The Julian century contains 36525 days and is represented by the symbol c. When possible, the notations in this document have been made consistent with ISO Standard 80000 on quantities and units. The numerical standards in Table 1.1 have been revised in order to conform to the new IAU (2009) System of Astronomical Constants adopted with IAU Resolution B2 (2009; *cf.* Appendix D.1).

The basis for this edition was set at an IERS Workshop on Conventions, held on September 20-21 2007 at the Bureau International des Poids et Mesures in Sèvres (France). This document and the associated information (*e.g.* software) essentially follow the recommendations specified in the executive summary of the workshop <[1]>. All electronic files associated with the IERS Conventions (2010) may be found on identical web pages maintained at the BIPM [2] (this pages will be referenced in this document) and at the USNO [3]. The recommended models, procedures and constants used by the IERS follow the research developments and the recommendations of international scientific unions. When needed, updates to this edition of the Conventions will be available electronically at the IERS Conventions Center website <[4]>. The principal changes between this edition and the IERS Conventions (2003) are listed in Section 0.2 below.

0.1 Models in the IERS Conventions

This section provides guidelines and criteria for models included in the IERS Conventions and for their usage in generating IERS reference products. All of the contributions used for generating IERS reference products should be consistent with the description in this document. If contributors to the IERS do not fully comply with these guidelines, they should carefully identify the exceptions. In these cases, the contributor provides an assessment of the effects of the departures from the

[1] `http://www.bipm.org/utils/en/events/iers/workshop_summary.pdf`
[2] `http://tai.bipm.org/iers/conv2010` and `ftp://tai.bipm.org/iers/conv2010`
[3] `http://maia.usno.navy.mil/conv2010` and `ftp://maia.usno.navy.mil/conv2010`
[4] `http://tai.bipm.org/iers/convupdt/convupdt.html`

conventions so that his/her results can be referred to the IERS Reference Systems. Contributors may use models equivalent to those specified herein if they assess the equivalence.

0.1.1 Classification of models

Models to represent physical effects can be classified into three categories:

Class 1 ("reduction") models are those recommended to be used *a priori* in the reduction of raw space geodetic data in order to determine geodetic parameter estimates, the results of which are then subject to further combination and geophysical analysis. The Class 1 models are accepted as known *a priori* and are not adjusted in the data analysis. Therefore their accuracy is expected to be at least as good as the geodetic data (1 mm or better). Class 1 models are usually derived from geophysical theories. Apart from a few rare exceptions, the models and their numerical constants should be based on developments that are fully independent of the geodetic analyses and results that depend on them. Whenever possible, they should preferably be in closed-form expressions for ease of use, and their implementation should be flexible enough to allow testing alternate realizations, if needed. A good example is the solid Earth tide model for station displacements (see Chapter 7).

Class 2 ("conventional") models are those that eliminate an observational singularity and are purely conventional in nature. This includes many of the physical constants. Other examples are the ITRF rotational datum, specifying the rotation origin and the rotation rate of the ITRF (see Chapter 4). As indicated by their name, Class 2 models may be purely conventional or the convention may be to realize a physical condition. When needed, choices among possible conventions are guided by Union resolutions and historic practice, which may differ in some cases.

Class 3 ("useful") models are those that are not required as either Class 1 or 2. This includes, for instance, the zonal tidal variations of UT1/LOD (see Chapter 8), as an accurate zonal tide model is not absolutely required in data analysis though it can be helpful and is very often used internally in a remove/restore approach. In addition, such a model is very much needed to interpret geodetic LOD results in comparisons with geophysical excitation processes, for instance. Class 3 also includes models which cannot (yet) fulfill the requirements for Class 1 such as accuracy or independence of geodetic results, but are useful or necessary to study the physical processes involved.

In the external exchange of geodetic results for the generation of IERS products, all Class 1 effects and specified Class 2 effects should be included, *i.e.* the models should be removed from the observational estimates. On the other hand, Class 3 effects should never be included in generating such results.

As much as possible, the documentation of the software provided by the IERS Conventions Center indicates the class associated with the model.

0.1.2 Criteria for choosing models

The IERS Conventions intend to present a complete and consistent set of the necessary models of the Class 1 and Class 2 types, including implemented software. Where conventional choices must be made (Class 2), the Conventions provide a unique set of selections to avoid ambiguities among users. The resolutions of the international scientific unions and historical geodetic practice provide guidance when equally valid choices are available. Class 3 models are included when their use is likely to be sufficiently common, as a guidance to users.

For station displacement contributions (Chapter 7), the Conventions clearly distinguish models which are to be used in the generation of the official IERS products from other (Class 3) models. Models in the first category, used to generate the IERS realization of the celestial and terrestrial reference systems and of the transformation between them, are referred to as "conventional displacement contributions." Conventional displacement contributions include Class 1 models (essential and geophysically based) that cover the complete range of daily and sub-daily variations, including all tidal effects, and other accurately modeled effects (mostly at longer periods). They relate the regularized positions of reference markers on the crust to their conventional instantaneous positions (see Chapter 4) and are described in Section 7.1. In addition, models for technique-specific effects, described in Section 7.3, relate the positions of reference markers to the reference points of instruments.

0.2 Differences between this document and IERS Technical Note 32

The structure of the IERS Conventions (2003) has been retained in this document, but the titles of some chapters have been changed, as indicated. Authors and major contributors of the previous (2003) version of the chapters may be found in the introduction to the Conventions (2003). The most significant changes from the previous version are outlined below for each chapter, along with the major contributors to the changes. These changes are also indicated in two tables that present the realization of reference frames and their accuracy estimates (Table 0.1) and the models along with estimates of the magnitude of the effects (Table 0.2).

The IERS Conventions are one of the products of the IERS Conventions Center. However, this volume would not be possible without the contributions acknowledged below for each chapter. In addition, we would also like to acknowledge the work of the Advisory Board for the IERS Conventions update, that was set up in 2005 under the chairmanship of Jim Ray to advise the Conventions Center in its work of updating the Conventions, with members representing all components of the IERS. Among those, special thanks are due to Ralf Schmid for providing detailed comments and corrections to nearly all chapters in this volume.

Table 0.1: Estimates of accuracy of reference frames

Ch.	Reference frame	Conventions 2003	Conventions 2010	Accuracy & difference/improvement between Conventions
2	celestial reference system & frame	ICRF-Ext.1	ICRF-2	Noise floor ≈ 40 μas (5 times better than ICRF-Ext.1). Axis stability ≈ 10 μas (twice as stable as ICRF-Ext.1). From 717 to 3414 total objects; from 212 to 295 "defining" sources
3	dynamical realization of ICRS	DE405	DE421	From 1 mas to 0.25 mas for alignment to ICRF
4	terrestrial reference system & frame	ITRF2000	ITRF2008	Accuracy over 1985-2008: 1 cm in origin, 1.2 ppb in scale. Most important systematic difference vs. ITRF2000: drift in z-direction by 1.8 mm/yr.

Table 0.2: Models of the Conventions (2010): some information on the magnitude of effects and changes vs. Conventions (2003). Sec. indicates the section number in this document; Cl. stands for Class (see section 0.1.1).

Sec.	Cl.	Phenomenon	Amplitude of effect	Conventions 2003	Conventions 2010	Accuracy & difference/improvement between Conventions
5	**Transformation between the ITRS and GCRS**					
5.5.1	1	libration in polar motion	tens of μas	No specific routine	Brzezinski PMSDNUT2 model	Specific routine
5.5.3	1	libration in the axial component of rotation	several μs in UT1	Not available	Brzezinski & Capitaine (2003) UTLIBR model	New model
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5.5.4	1	precession-nutation of the CIP	tens of as/yr and tens of as for the periodic part in X and Y	IAU2000 PN	IAU2006/2000 PN	100 μas/c. + 7 mas/c.^{2} in X; 500 μas/c. in Y
5.5.5	3	FCN	Few hundred μas	not available	Lambert model	Accuracy: 50 μas rms, 100 μas at one year extrapolation
5.5.6	1	space motion of the CIO	mas/c.	IAU2000 PN	IAU2006/2000 PN	no change larger than 1 μas after one century
6	**Geopotential**					
6.1	1	Global geopotential model	10^{-3} of central potential	EGM96	EGM2008; C20 and rates of low degree coefs from other sources	EGM96: degree and order 360; EGM2008: complete to degree and order 2159; rate terms for low degree coefs.
6.2	1	Solid Earth tides	10^{-8} on C_{2m}, 10^{-12} on C_{3m}, C_{4m}	Eanes *et al.*, 1983; Mathews *et al.*, 2002	Unchanged	No change
6.3	1	Ocean tides	For LEO orbit integration: decimetric over 1 day	CSR 3.0	FES2004; Treatment of secondary waves specified	Effect of new model for LEO / MEO: few mm over several days integration; Treatment of secondary waves for LEO: 20% of total effect
6.4	1	Solid Earth pole tide	10^{-9} on C_{21}, S_{21}	Centrifugal effect vs. conventional mean pole (2003)	Centrifugal effect vs. conventional mean pole (2010)	Change of conventional mean pole: effect of a few 10^{-11} on C_{21}, S_{21}
6.5	1	Ocean pole tide	Few 10^{-11} on low degree coefs	Not available	Desai (2002)	New model
7	**Displacement of reference points**					
7.1.1	1	Solid Earth tides	decimetric	Conventional routine from Dehant & Mathews	Unchanged	No change
7.1.2	1	Ocean loading	centimetric	Loading response from Scherneck (several tide models); no conventional implementation.	Loading response from Scherneck (several tide models); Implementation by Agnew software (342 constituent tides)	
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7.1.3	1	S1-S2 Atmospheric pressure loading	millimetric	not available	Implementation of Ray & Ponte (2003) by vanDam	New model
7.1.4	1	Conventional mean pole	Hundreds of mas	linear model	cubic model from 1976.0 until 2010.0; linear model after 2010.0	tens of mas.
7.1.4	1	Pole tide	2 cm radial, few mm tangential	Centrifugal effect vs. conventional mean pole (2003)	Centrifugal effect vs. conventional mean pole (2010)	Change of conventional pole: effect may reach 1 mm
7.1.5	1	Ocean pole tide loading	2 mm radial, $<$ 1 mm tangential	Not available	Desai (2002)	New model
7.3.1	3	Reference points of instruments: effect of temperature and pressure	$\sim$ 1 mm	Not specified	Reference temperature and pressure: GPT model, Boehm *et al.* (2007)	Between using average *in situ* temperature measurements and GPT: $<$ 0.5 mm site height change due to antenna thermal deformation
7.3.2	1	Thermal deformation of VLBI antenna	$>$ 10 ps on VLBI delay, several mm variation in coordinates	Nothnagel *et al.* (1995)	Nothnagel (2009)	Reference temperatures defined according to GPT model; reduction in annual scale variations of about 1 mm
7.3.3	1	GNSS antenna phase center offsets and variations	decimetric	Not specified	Schmid *et al.* (2007)	10^{-9} on scale; tropospheric zenith delay and GPS orbit consistency improved
8	**Tidal variations in the Earth's rotation**					
8.1	3	Zonal tides on UT1	785 μs at M_f	Defraigne and Smits (1999) 62 terms	Combination of Yoder *et al.* (1981) elastic body tide, Wahr and Bergen (1986) inelastic body tide, and Kantha *et al.* (1998) ocean tide models	6 μs at M_f
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8.2	1	Subdaily tides	$\sim$ 0.5 μas for PM $\sim$ 0.05 ms for UT1	Ray *et al.* (1994); conventional implementation by Eanes	No change	No change
8.3	3	long-period tides, polar motion	(pro-grade,retrograde) polar motion amplitude of (66, 74) μas at M_f	Not available	Dickman and Nam (1995), Dickman and Gross (2009)	(prograde, retrograde) polar motion amplitude of (66, 74) μas at M_f
9	**Models for atmospheric propagation delays**					
9.1	1	Troposphere; optical	$\sim$ 2.2 m at zenith to $\sim$ 14 m at 10° above horizon	Marini and Murray (1973)	Mendes and Pavlis (2004) zenith delay; Mendes and Pavlis (2003) "Fcul" mapping function (MF)	more accurate delays below 20° elevation and all the way to 3° above horizon; accurate to $\sim$ 7 mm (Total error due to ZTD and MF)
9.2	1	Troposphere; radio	Hydrostatic zenith delays $\sim$ 2.3 m Wet zenith delays typically $\sim$ 10–150 mm	Several MF *e.g.* Neill (1996) or Lanyi (1984)	MF: VMF1 based on 6-hour ECMWF data. GMF based only on latitude, site height, time of year (Boehm *et al.*, 2006)	Both VMF1 and GMF remove latitude-dependent mapping function bias (average $\sim$ 4 mm in site height). VMF1 reduces short-term vertical scatter (average $\sim$ 4–5 mm)
9.2	1	Troposphere; horizontal gradients	can lead to systematic errors in the scale of estimated TRF at level of $\sim$ 1 ppb	Not available	J. Boehm APG a priori model	New model
9.4	1	Ionosphere; radio: First order term	can reach 100 ns for GPS	Not available	Sources for Vertical TEC + conventional mapping function	New model
9.4	1	Ionosphere; radio: Higher order terms for dual-frequency	can reach 100 ps for GPS; a few ps for wide-band VLBI	Not available	Conventional model based on Slant TEC + Magnetic field model	New model
10	**General relativistic models for spacetime coordinates and equations of motion**					
10.1	2	Time coordinates	TCB, TDB in barycentric; TCG, TT in geocentric	IAU1991-IAU2000	IAU1991-IAU2000; IAU2006 TDB definition	New TDB definition
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10.1	1	TCB-TCG transformation	1.5 ms annual; 2 μs diurnal on Earth	FB2001; TE405; HF2002	HF2002_IERS	HF2002_IERS vs. HF2002: 1.15×10^{-16} in rate;
10.2	1	transformation between proper time and coordinate time near Earth	GNSS: frequency shift of $\sim$ 4-5$\times 10^{-10}$ + periodic term of several tens of ns	Not specified	Conventional GNSS model specified; Information on next most significant term.	New model
11	**General relativistic models for propagation**					
11.1	1	VLBI delay	tens of ms	conventional 'consensus' model	no change	Uncertainty of model: 1 ps
11.2	1	time of propagation for ranging techniques	up to a few s	conventional model	no change	Uncertainty of model: 3 ps

Chapter 1: General definitions and numerical standards

The section "Numerical standards" has been re-written and the list of constants ensures consistency with the IAU (2009) system of astronomical constants. It is derived mostly from the work of the IAU Working Group on Numerical Standards of Fundamental Astronomy, headed by B. Luzum.

Chapter 2: Conventional celestial reference system and frame

This chapter has been rewritten to present the second realization of the ICRF, following the work of the IAU working group with the same name, headed by C. Ma. The primary contributors are E. F. Arias, S. Bouquillon, A. Fey, G. Francou and N. Zacharias.

Chapter 3: Conventional dynamical realization of the ICRS

The chapter has been re-written (with W. M. Folkner as the primary contributor) and provides information on recently released ephemerides. When a conventional choice is needed, DE421 is recommended to provide continuity for implementation by users.

Chapter 4: Terrestrial reference systems and frames

The chapter (with a new title) has been significantly rewritten with Z. Altamimi and C. Boucher as the primary authors. It incorporates the new realization ITRF2008, which was introduced in 2010.

Chapter 5: Transformation between the International Terrestrial Reference System and Geocentric Celestial Reference System

The chapter (with a new title) has been significantly rewritten, with N. Capitaine and P. Wallace as the primary authors, in order to make the chapter compliant with the IAU 2000/2006 resolutions and the corresponding terminology. A presentation of the IAU 2006 resolutions has been added, and a description of the models, procedures and software to implement the IAU 2000/2006 resolutions has been included. The organization of the chapter has been modified in order to clarify the successive steps to be followed in the coordinate transformation. Additional contributors include A. Brzeziński, G. Kaplan and S. Lambert.

Chapter 6: Geopotential

A new conventional geopotential model based on EGM2008 is presented. The section on ocean tides has been rewritten and a new section describes the oceanic pole tide. The primary contributors are S. Bettadpur, R. Biancale, J. Chen, S. Desai, F. Flechtner, F. Lemoine, N. Pavlis, J. Ray and J. Ries.

Chapter 7: Displacement of reference points

A new conventional mean pole model, to be referenced as the IERS (2010) mean pole model, is given consistently with Chapter 6. The section on ocean loading has been rewritten and new sections describe the oceanic pole tide loading and the S1-S2 atmospheric loading. The section "Models for the displacement of reference points of instruments" has been updated: It contains models for a reference temperature, the thermal expansion of VLBI antennas and GNSS antenna phase center offsets and variations. The primary contributors are D. Agnew, J. Boehm, M. Bos, T. van Dam, S. Desai, D. Gambis, A. Nothnagel, G. Petit, J. Ray, H.-G. Scherneck, R. Schmid, and J. Wahr.

Chapter 8: Tidal variations in the Earth's rotation

The model to evaluate the effects of zonal Earth tides on the Earth's rotation has been updated, with software included, and a model to evaluate tidal variations in polar motion and polar motion excitation due to long period ocean tides has been added. The primary contributors are C. Bizouard and R. Gross.

Chapter 9: Models for atmospheric propagation delays

This chapter (with a new title) has been completely rewritten. The models for tropospheric delay have been updated and a new section "Ionospheric models for radio techniques" has been added. The primary contributors are J. Boehm, M. Hernández Pajares, U. Hugentobler, G. Hulley, F. Mercier, A. Niell, and E. Pavlis.

Chapter 10: General relativistic models for space-time coordinates and equations of motion

The chapter has been updated following IAU Resolution B3 (2006) and the new description of the relations between time scales. A new section "Transformation between proper time and coordinate time in the vicinity of the Earth" and numerical examples have been added. The primary contributors are U. Hugentobler, J. Kouba, S. Klioner, R. Nelson, G. Petit, J. Ray, and J. Ries.

Chapter 11: General relativistic models for propagation

The chapter has been updated for minor wording corrections.

0.3 Conventions Center

At the time of this edition, the IERS Conventions Center is composed of E. F. Arias, B. Luzum, D. D. McCarthy, G. Petit and B. E. Stetzler. P. Wolf has also contributed over past years.

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